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MEASUREMENT OF THE UHECR ENERGY SPECTRUM USING DATA FROM THE SURFACE DTETCTOR OF THE PIERRE AUGER OBSERVATORY

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Abstract. We report a measurement of the cosmic ray energy spectrum based on the high statistics collected by the surface detector of the Pierre Auger Observatory. High-energy cosmic rays are measured by recording the extensive air shower of secondary particles they produce in the atmosphere. The properties of the CR, such as its energy, have to be inferred from the air showers. The methods developed to determine the spectrum from reconstructed observables are described in detail. The hybrid nature of the Pierre Auger Observatory, which combines a fluorescence detector and a surface detector, allows the energy calibaration of the observables. The methods are simple and robust and do not rely on detailed numerical simulation or any assumption about the chemical composition of the CRs.

1 Introduction

The Pierre Auger Observatory (Abraham et al. 2004), located near Malargüe, Argentina (35.2° S, 69.5°W) at 1400 m a.s.l., is designed to study cosmic rays (CRs) from $\approx 10^{18}$ eV up to the highest energies. Two different techniques are used to detect the extensive air showers (EAS) initiated by the highest energy CRs. Firstly, a collection of telescopes is used to collect the fluorescence light emitted from nitrogen excited by charged particles. The fluorescence detector (FD) provides a nearly calorimetric, model-independant energy measurement, because the ultra-violet light is proportional to the energy deposited by the EAS along its path. This method can be used only when the sky is moonless and dark, and thus has roughly a 10% duty cycle (Dawson 2007). The second method uses 1600 water-Cherenkov detectors to sample the photons and charged particles of the EAS at ground level. It is laid out over 3000 km^2 on a triangular grid of 1.5 km spacing. The surface detector (SD) trigger condition, based on a 3-stations coincidence, makes the array fully efficient above about 3×10^{18} eV. The signal at a 1000 m core distance, S(1000), is used to estimate the primary energy. The SD, with its near 100% duty cycle, gives the large sample used here (Suomijarvi et al. 2007). A subsample of EAS detected by both instruments, the hybrid events, are very precisely measured (Perrone et al. 2007) and provide an invaluable energy calibration tool. Indeed, the comparison of the shower energy, measured using the FD, with the S(1000) for the hybrid events is used to calibrate the energy scale for the SD.

2 Analysis procedure

A cosmic ray of 10^{19} eV arriving vertically typically produces signals in 8 stations. Signals are quantified in terms of the response of a water tank to a single relativistic muon passing vertically and centrally through it (a vertical equivalent muon or VEM). Calibration of each sations is carried out continuously with 2% accuracy (Bertou 2006). The signals are fitted in each event to find the VEM size at 1000 m (Newton 2006). The uncertainty in every S(1000) is found, accounting for statistical fluctuations of the signals, systematic uncertainties in the assumption of the fall-off of the signal with distance and the shower-to-shower fluctuations (Ave et al. 2007). Above 10^{19} eV the uncertainty in S(1000) is about 10%.

The longitudinal development of EAS in the atmosphere is measured using the fluorescence detectors. The light produced is detected as a line of illuminated pixels in one or more fluorescence telescope cameras. The

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signal, after correcting for attenuation due to Rayleigh and aerosol scattering, is proportional to the number of fluorescence photons emitted in the field of view of the pixel. Cherenkov light produced at angles close to the shower axis can be scattered towards the pixels: this contamination is accounted for (Unger et al. 2007). A Gaisser-Hillas function (Gaisser & Hillas 1977) is used to reconstruct the shower profile which provides a measurement of the energy of the EAS deposited in the atmosphere. To derive the primary energy, an estimate of the missing energy carried into the ground by muons and neutrinos must be made based on assumptions about the mass of cosmic rays and of the appropriate hadronic model. For a primary beam mixture of protons and iron, simulations of showers with the QGSJET01 model indicate a correction of 10% (Barbosa et al. 2004). The systematic uncertainty is 4%. Systematic uncertainties in the FD energy measurement have been estimated. Measurements, made in combination with the fluorescence detectors, are used to measure the quality and transmission properties of the atmosphere. In particular, the vertical aerosol optical depth (VAOD) profile (Ben-Zvi et al. 2007) is found every 15 min by observing the light scattered from a centrally-located laser yielding an hourly average. The average correction to E_{FD} from the VAOD measurement is +5% at 3×10^{18} eV rising to +18% at 5×10^{19} eV, reflecting the increase of the average distance of such events from an FD. The largest uncertainties are in the absolute fluorescence yield (14%), the absolute calibration of the FD (10%) and the reconstruction method (10%). Systematic uncertainties from atmospheric aerosols, the dependence of the fluorescence spectrum on temperature and on humidity are each at the 5% level. These uncertainties are independent and added in quadrature give 22% for E_{FD}.

The present data set is taken from 1 January 2004 to 31 August 2007 while the array has been growing from 154 to 1388 stations. Only events with zenith angle $\theta < 60°$ and reconstructed energy $E > 3 \times 10^{18}$ eV are considered. Candidate showers are selected on the basis of the topology and time compatibility of the triggered detectors (Allard et al. 2005). The SD with the highest signal must be enclosed within an active hexagon, in which all six surrounding detectors were operational at the time of the event. Thus it is guaranteed that the intersection of the axis of the shower with the ground is within the array, and that the shower is sampled sufficiently to make reliable measurements of $S(1000)$ and of the shower axis. For this analysis, the array is fully efficient, so the acceptance at any time is determined by the geometric aperture of the array (Allard et al. 2005). The integrated exposure reaches 6992 km^2 sr yr, which is a factor of 2 and 3 larger than the exposure obtained by HiRes (Abbasi et al. 2008) and AGASA (Takeda et al. 2003), respectively.

The decrease of $S(1000)$ with zenith angle arising from the attenuation of the shower and from geometrical effects is quantified by applying the constant integral intensity cut method (Hersil et al. 1961), justified by the approximately isotropic flux of primaries. An energy estimator for each event, independent of θ, is S_{38°, the $S(1000)$ that EAS would have produced had it arrived at the median zenith angle, 38°. Using information from the fluorescence detectors the energy corresponding to each S_{38° can be estimated almost entirely from data except for assumptions about the missing energy. The energy calibration is obtained from a subset of high-quality hybrid events (Perrone et al. 2007). Statistical uncertainties in S_{38° and E_{FD} were assigned to each event: averaged over the sample these were 16% and 8%, respectively. The correlation of S_{38° with E_{FD} is shown in Fig. 1 (left), together with the least-squares fit of the data to a power-law, $E_{FD} = a \cdot S_{38^\circ}^b$. The best fit yields $a = (1.49 \pm 0.06(\mathrm{stat}) \pm 0.12(\mathrm{syst})) \times 10^{17}$ eV and $b = 1.08 \pm 0.01(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ with a reduced χ^2 of 1.1. S_{38° grows approximately linearly with energy. The energy resolution, estimated from the fractional difference between E_{FD} and the derived SD energy, $E = a \cdot S_{38^\circ}^b$, is shown too in Fig. 1 (right). The root-mean-square deviation of the distribution is 19%, in good agreement with the quadratic sum of the S_{38° and E_{FD} statistical uncertainties of 18%. The calibration accuracy at the highest energies is limited by the number of events: the most energetic is $\sim 6 \times 10^{19}$ eV. The calibration at low energies extends below the range of interest.

The energy spectrum based on $\sim 20,000$ events is shown in Fig. 2. Statistical uncertainties and 84% confidence-level limits are calculated according to (Feldman & Cousins 1998). Systematic uncertainties on the energy scale due to the calibration procedure are 7% at 10^{19} eV and 15% at 10^{20} eV, while a 22% systematic uncertainty in the absolute energy scale comes from the FD energy measurement. The spectrum is fitted by a smooth transition function with the suppression energy of 4×10^{19} eV defined as that at which the flux falls below an extrapolated power law by 50%. To examine the spectral shape at the highest energies, we fit a power-law function between 4×10^{18} eV and 4×10^{19} eV, $J \propto E^{-\gamma}$, using a binned likelihood method (Hague et al. 2007). A power-law is a good parameterization: the spectral index obtained is $2.69 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{syst})$

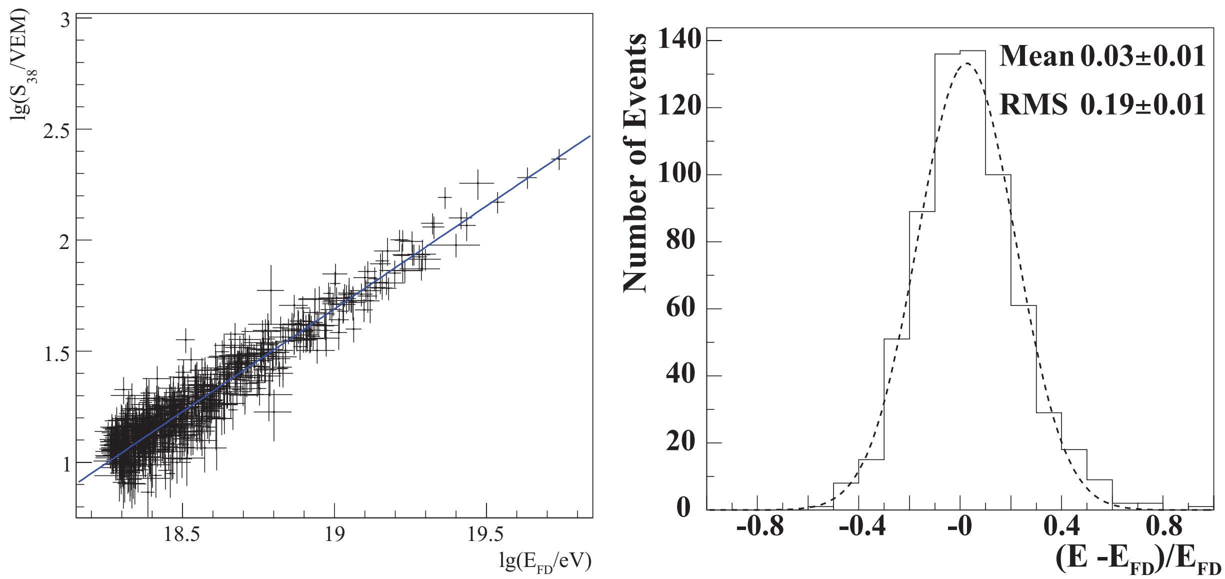

Fig. 1. Left: Correlation between $\lg S_{38^\circ}$ and $\lg E_{FD}$ for the 661 hybrid events used in the fit. The full line is the best fit to the data. Right: the fractional differences between the two energy estimators.

(reduced $\chi^2 = 1.2$), the systematic uncertainty coming from the calibration curve. The numbers expected if this power-law were to hold above 4×10^{19} eV or 10^{20} eV, would be 167 ± 3 and 35 ± 1 while 69 events and 1 event are observed. The spectral index above 4×10^{19} eV is $4.2 \pm 0.4(\text{stat}) \pm 0.06(\text{syst})$. A method which is independent of the slope of the energy spectrum is used to reject a single power-law hypothesis above 4×10^{18} eV with a significance of more than 6 standard deviations, a conclusion independent of the systematic uncertainties currently associated with the energy scale. In Fig. 2 the fractional differences with respect to an assumed flux $\propto E^{-2.69}$ are shown. HiRes I data (Abbasi et al. 2008) show a softer spectrum where our index is 2.69 while the position of suppression agrees within the quoted systematic uncertainties.

3 Conclusion

We reject the hypothesis that the cosmic-ray spectrum continues with a constant slope above 4×10^{19} eV, with a significance of 6 standard deviations. This result is independent of the systematic uncertainties in the energy scale. A precise measurement of the energy spectrum, together with anosotropy and mass composition studies in this energy range, will shed light on the origin of the highest energy particles observed in nature.

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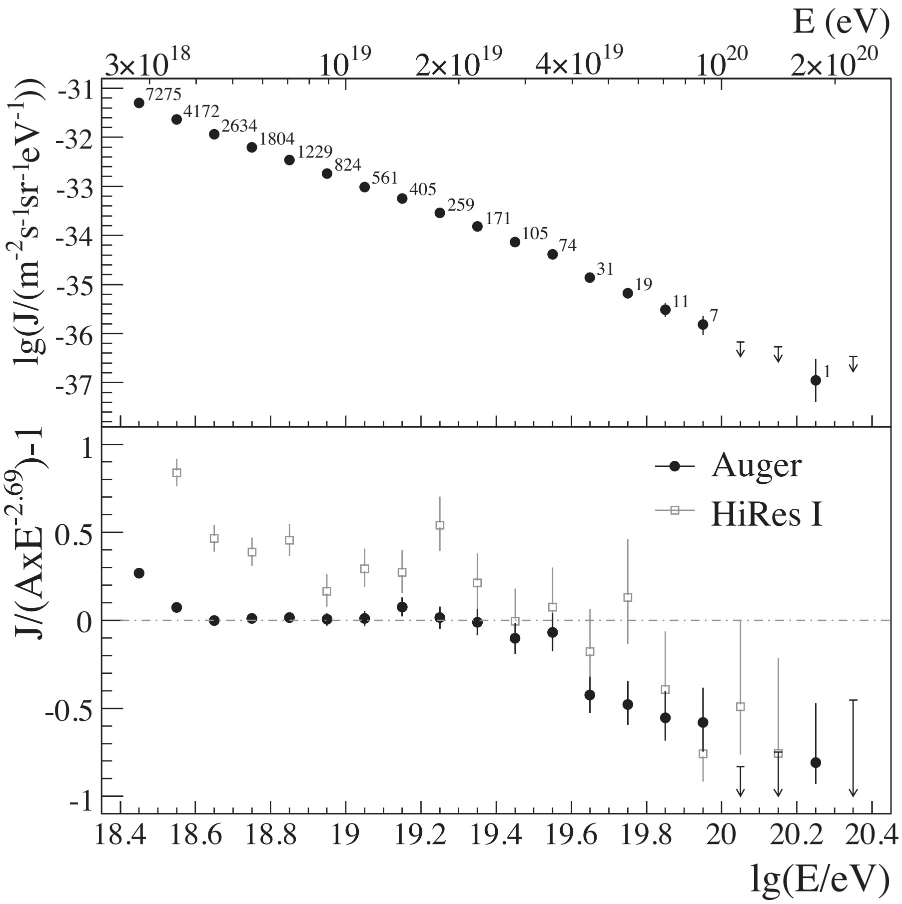

Fig. 2. Upper panel: The differential flux J as a function of energy, with statistical uncertainties. Lower Panel: The fractional differences between Auger and HiRes I data (Abbasi et al. 2008) compared with a spectrum with an index of 2.69.

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